BI-DIRECTIONAL OPTICAL TRANSMISSION USING DUAL CHANNEL BANDS

FIELD OF THE INVENTION

The present invention relates generally to optical communications systems and more particularly to optical communications systems providing communications over a single optical fiber.

BACKGROUND OF THE INVENTION

Bi-directional optical communications systems of the prior art which are capable of two-way transmission over a single optical fiber typically employ wavelength division multiplexing to separate and distribute the communications traffic over a number of distinct wavelengths. One prior art method of single fiber bi-directional optical communications employs wavelength interleaving, where wavelengths traveling in a first direction are interleaved with wavelengths traveling in a second direction. For instance, incremental wavelengths designated as λ_1, λ_3, λ_5, etc. are set up to travel in the first direction, whereas within the same spectral band, wavelengths λ_2, λ_4, λ_6, etc. travel in the second direction.

Another form of bi-directional communication interleaves multiple sub-bands or blocks of related wavelengths. For example, wavelengths $\lambda_{1\text{-}4}$ may be set up to travel in a first direction, wavelengths $\lambda_{5\text{-}8}$ to travel in a second direction, wavelengths $\lambda_{9\text{-}12}$ to travel in the first direction, wavelengths $\lambda_{13\text{-}16}$ to travel in the second direction and so on. In each of the above cases, all of the wavelengths that are utilized are found within the same frequency band, for example, the C-band. Each of the methodologies employs multiple filters in each sub-band in order to process the multiple wavelengths. A consequence is that the presence of the multiple filters produces relatively large overall signal losses. A further consequence is that the loss in the multiple filters can be optimized for only one sub-band in each direction. Accordingly, there is a need for a system that provides decreased signal losses over a wider band of wavelengths/frequencies.

SUMMARY OF THE INVENTION

A bi-directional optical transmission system according to the present invention provides transport of x optical channels over n nodes. The system supports two-way transport of the x channels over a single fiber connecting each of the nodes in sequence. The system is advantageous in that only two optical transmission bands are utilized in order to achieve minimal loss in the separation of signals in the two bands. The two directions of optical transmission within the system have a spectral (wavelength/frequency) separation, in addition to directional separation. The use of only two bands permits the utilization of low-loss wide band thin film optical filters to combine and separate the signals at each node. Further processing of the signals takes place in unidirectional components, e.g., multiplexers, demultiplexers and amplifiers, as required. An alternating arrangement of the optical filters in the two separate bands is chosen to maximize the optical performance of the overall system and significantly reduce insertion losses.

In one exemplary embodiment of the present invention, at each intermediate node in the system, a transmission filter for the first band of optical signals is used between the output of an optical amplifier for the first band and the bi-directional fiber. A reflection port of this filter is used to carry oppositely directed signals of the second band from the bi-directional fiber to an optical amplifier for the second band. An optical transmission filter for the second optical band is also used at each intermediate node between the output of an optical amplifier for the second band and the bi-directional fiber. The reflection port of the second band filter is used to carry the input signal of the first band from the bi-directional fibers to the optical amplifier for the first band. End nodes in the system include only an appropriate one of the transmission filters. The alternate arrangement of filters simultaneously provides for optimal signal performance for both directions of transmission at every node in the system while at the same time minimizing insertion losses from filtering components.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention may be obtained from consideration of the following detailed description of the invention in conjunction with the drawing, with like elements referenced with like references, in which:

FIG. 1 is an exemplary embodiment of a bi-directional optical transmission system in accordance with the present invention.

DETAILED DESCRIPTION

Referring to Fig. 1, there is shown one exemplary embodiment of a bi-directional fiber transmission system 10 in accordance with the present invention. The system 10 provides transport of *x* channels between a first end node 12 and a second end node 14 at different locations. An intermediate node, or a repeater node 16, is shown coupled between the first and second end node 12, 14. It would be understood that any number of intermediate nodes can be coupled in the signal path between the two end nodes in order to maintain appropriate optical transmission levels. Accordingly, a complete bi-directional fiber transmission system includes a total of *n* nodes. It would also be understood that intermediate nodes may be more than just repeater type nodes and can include pairs of end nodes as well as optical add and drop nodes. In principal, end nodes 12, 14 could be located in the same office and the traffic (structure) connected between them so as to form a complete ring system and not just a simple linear connected chain of nodes. Optical fiber 18 for carrying the bi-directional signals transmitted through the system is coupled between each of the nodes.

The present invention is advantageous in that only two transmission bands, for example, the "C" band in one direction and the "L" band in the other direction, are utilized in order to achieve minimal loss in the separation of signals in the two bands. As is known by those skilled in the art, the C-band generally includes wavelengths in the range of 1530 to 1563 nm and the L-band generally includes wavelengths in the range of 1573 to 1610 nm. The two directions of optical transmission on the fiber 18 between the end nodes 12, 14 have a spectral (wavelength/frequency) separation, in addition to directional separation. The use of only two bands permits the utilization of low-loss wide

band thin film optical filters to combine and separate the signals at each node. Further processing of the signals takes place in unidirectional components, e.g., multiplexers, demultiplexers and amplifiers, as required. As shown in Fig. 1, the signals in the C-band propagate from the first end node 12 to the second end node 14, while signals in the L-band propagate from the second end node 14 to the first end node12.

At the first end node 12, a given number, *x*, of optical translator units 20 receive incoming signals from the *x* corresponding wavelength channels. The optical translator units 20 (OTUs) translate the incoming wavelengths (typically 1310 nm) to an appropriate wavelength in the C-band (typically in the range of 1530nm to 1563nm). The OTUs 20 are coupled to an optical multiplexer 22 unit which is in turn coupled to an optical amplifier unit 24. These C-band signals are spectrally combined in the optical multiplexer 22 and then amplified via the optical amplifier 24. The output of the optical amplifier 24 couples to an input port 26 of a combiner/separator unit 30 designated in the figure as "COMSEP". As its name implies, the COMSEP 30 combines optical signals traveling in a first direction and separates optical signals traveling in the opposite direction. As shown, the COMSEP includes a single band input port 26, a single band output port 28 and a bi-directional input/output port 32. The single band ports 26, 28 act as inputs and outputs for optical signals of the predefined signal bands traveling in a single direction. In addition, although referred to as single band input and output ports it would be understood that these terms are not meant to be limiting with regard to the specific construction of the ports themselves. That is, the ports are referenced in such a manner so as to provide clarification as to the predominate direction of signal flow throughout the system 10. Internally, the COMSEP unit 30 of the first end node 12 includes a C-band transmission filter 34. A COMSEP containing a C-band transmission filter may be generally referenced as a "C-band COMSEP " in later portions of the document. As will be explained, the C-band filter 34 enables the C-band signals to be transmitted to the bi-directional input/output port 32 of the COMSEP 30 with low insertion loss.

As would be understood, both C-band and L-band signal bands are present at the bi-directional input/output port 32 of the COMSEP 30 and within the fiber 18 connecting between each of the nodes. The C-band signals propagate from the first end node 12

through the intermediate nodes 16 to the second end node 14 on this common fiber 18. At the first end node 12, incoming L-band signals arriving on the bi-directional input/output port 32 are reflected from the C-band filter 34 of the COMSEP 30 and are output through the single band output port 28. The single band output port 28 of the first COMSEP 30 couples to an L-band optical amplifier 36 which in turn couples to an optical demultiplexer (DEMUX) 38. The L-band signals are amplified within the optical amplifier 36 and then spectrally separated in the demultiplexer 38. In converse functionality to the C-band OTUs, L-band optical translator units 40 couple to the outputs of the optical demultiplexer 28 for converting the L- band signals back to a nominal wavelength (typically 1310nm).

A first repeater node 16 couples to the bi-directional input/output port 32 of the first end node 12. As shown, the repeater node 16 includes two combiner/separator units (COMSEPs) 42, 44 and two optical amplifiers 46, 48 (one each for the L-band and one each for the C-band). As with the COMSEP 30 of the first end node 12, each COMSEP 42, 44 of a repeater node 16 includes a bi-directional input/output port 50, 51 a single band input port 52, 53 and a single band output port 54, 55, respectively. The COMSEP 30 of the first end node 12 which includes the C-band filter 34 couples to a COMSEP 42 in the repeater node 16 that includes an L-band transmissive filter 56. A COMSEP containing an L-band transmission filter may be generally referenced as an "L-band COMSEP " in later portions of the document. As will be discussed, the alternating arrangement of single-band C-band and L-band filters within the COMSEP units of each subsequent node provides advantages with regard to reduction of insertion loss for filters.

As would be understood by those skilled in the art, depending on the distance between the two end nodes, a given number of repeaters may be located between the first end node 12 and the second end node 14. The second end node 14 is essentially a complementary image of the first end node. That is, whereas the COMSEP 30 of the first end node 12 includes a C-band transmission filter 34, the COMSEP 60 of the second end node 14 includes an L-band transmission filter 62. Similarly, the optical amplifiers, multiplexers, demultiplexers and optical translator units are all adapted to the alternate band wavelengths. The second end node 14 couples to the bi-directional fiber 18 through the bi-directional input/output port 64 of the L-band COMSEP 60. The single band

output port 68 of the L-band COMSEP 60 in the second end node 14 couples to an optical amplifier 72 which then couples to an optical demultiplexer 74. C-band optical translator units 76 couple to the outputs of the optical demultiplexer 74 for translating the outputs of the optical demultiplexer back to their nominal 1310 nm wavelength.

On the input side of the second end node, optical translator units (OTUs) 78 are included for converting incoming wavelengths to an appropriate wavelength in the L–band. As shown, the OTUs couple to an optical multiplexer 80 and an optical amplifier 82. The optical amplifier 82 couples to the single band input port 70 of the L-band COMSEP 60 of the second end node 14.

Having described the basic structure of the bi-directional transmission system 10, the operation of the present invention can now be described greater detail. Beginning with the first end node 12, incoming wavelengths, e.g., 1310 nm, enter the optical translator units 20 (OTUs) and are translated to an appropriate wavelength in the C-band (e.g., in the range of 1530nm to 1563nm). These C-band signals are spectrally combined in the optical multiplexer 22 and then amplified via the optical amplifier 24. The C-band signals are sent to a C-band transmission optical filter 34 at the single band input port 26 in the COMSEP 30. The filter transmits these C-band signals to the bi-directional port with a low insertion loss. With regard to the C-band COMSEP 30, filters are available today with 1.7 dB insertion loss for the worst case under all operating conditions and with 1.3 dB for typical performance at the exemplary target frequencies specified herein. The loss is calculated based on a 1.5 dB transmission loss and an approximate 0.2 dB loss for two connectors. Filters having the above characteristics are available from suppliers such JDS Uniphase of San Jose, California and E-TEK Dynamics, Inc. of San Jose, California.

The C-band signals propagate from the first end node 12 to an intermediate node 16 on this common fiber 18. Some portion of the C-band signal may change direction in the common fiber due to a variety of causes including imperfect splices, poor connectors, or even non-linear fiber properties. However, most of these reflected C-band signals that happen to change direction and return to the first end node 12 will be routed by the C-band filter 34 of the COMSEP 30 from the bi-directional port 32 to the single band input port 26. A minimal signal level will be transmitted from the bi-directional port to the output port 28 as determined by the performance of the optical filter used. For example,

the suggested filter components will deliver -15dB or better performance worst case for this parameter. When combined with the worst case spectral performance of the optical amplifier 36 and demultiplexer 38, those skilled in the art would see that no additional spectral filtering is needed for reasonable levels of reflected C-band signals.

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At the repeater node 16, the C-band signals from the first end node 12 enter the L-band COMSEP 42 through its bi-directional port 50. This COMSEP 42 has an L-transmission filter 56 and therefore, as shown, the C-band signals reflect off the L-band filter to the output port 52 54 with minimal insertion loss. L-band filters for this application are available with 0.9dB for the worst case insertion loss under all operating conditions and with 0.3-0.5dB typical performance. The loss is calculated based on a 0.7 dB transmission loss and an approximate 0.2 dB loss for two connectors. The C-band signals are amplified in the optical amplifier 46 and then directed to the input port 53 of the C-band COMSEP 44. The C-band signals are propagated from this repeater node 16 to the ~~next node in the system in this manner.~~

C-band signals exiting the output port of a C-band COMSEP in a last repeater node enter an L-band COMSEP 60 in the second end node 14 through its bi-directional port 64. As shown, the C-band signals reflect off this filter 62 to the output port 68, again with minimal insertion loss. The COMSEP 60 is coupled to an optical amplifier 72, which is in turn coupled to a demultiplexer (DEMUX Cn) 74. The C-band signals are amplified in the optical amplifier 72 and then spectrally separated in the demultiplexer 74. The C-band signals are then spectrally converted back to a nominal wavelength (typically 1310nm) utilizing the OTU units 76 (cn1 through cnx).

In a similar manner to the C-band signals, nominal wavelength input signals (typically 1310 nm) entering the L-band OTUs 78 in the second end node 14 are translated to appropriate L-band wavelengths (typically in the range of 1573nm to 1610nm). The signals are then propagated from the second end node 14 to the first end node 12 in a similar manner to that described with respect to the C-band signals. At the first end node 12 the L-band signals reflect off of the C-band filter 34 in the COMSEP 30. The L-band signals are amplified in the optical amplifier 36 and then spectrally separated in the demultiplexer 38 (DEMUX L1). The L-band signals are then spectrally

converted back to a nominal wavelength (typically 1310nm) utilizing the OTU units 40 (111 through 11x).

The alternating use of C and L transmission filters as described with respect to present invention provides several important advantages to the overall system. The most apparent is that bi-directional transmission on the single fiber between the nodes is realized. This reduces the required fiber to make a two way connection between two network elements by half compared to the current practice in many systems. Understandably, this is a very significant cost saving for customers.

Use of the alternating arrangement of the filters as shown in accordance with the present invention also results in a minimum optical insertion loss at the point of the separation of the low level input signal at each node. This is true for both directions of transmission and is a direct consequence of alternating the filters as described. As can be seen from the Fig. 1, C-band signals traveling from the first end node 12 to the second end node 14 are always separated using a reflection path in an L-band COMSEP. Similarly, L-band signals traveling from the second end node 14 to the first end node 12 are always separated using a reflection path in a C-band COMSEP. Minimizing insertion loss at the point of separation of the bands is critically important because any extra insertion loss at this point is difficult to recover in the system level optical power budgets. This difficulty arises today in real systems because the high power levels that are used for the optical signals launched into the fiber 18 give rise to many corrupting undesirable non-linear effects in the optical fiber between the nodes of the systems. Therefore, the signal launch power levels into fiber 18 are limited and cannot be increased to make up for additional separation loss.

The alternating arrangement of the filters as shown also enables the insertion loss at the launch side filter to be recovered by having a higher power optical amplifier output without incurring non-linear optical power penalties in the outside fiber plant. This is possible because the fiber lengths used between the output of the optical amplifier and the input of the COMSEP are short and, therefore, the optical power penalties due to the higher power until the loss of the COMSEP is encountered are quite negligible.

The system optical power budget is a critical parameter in determining the maximum distance between the optical translator units as it has a direct bearing on the

realized system optical signal to noise ratio. In typical systems, a reduction by one half of the noise contribution per span (-3 dB) can be utilized to double the number of spans (+3 dB) before an optical translator unit must be used to regenerate the signal. A system in accordance with the present invention has a 0.8 dB to 4 dB advantage for the optical power budget over the equivalent unidirectional system. This advantage is a function of the specific limitation that a unidirectional system encounters and can be used to either increase the permitted span loss or to increase the maximum number of spans between regeneration of the signals.

The use of only two (2) bands is required to achieve this minimal separation loss. Hence, each band must be wide to support a maximum number of channels. Practical systems today offer channels covering 3-4 THz of spectrum in each band. The selection of wavelengths used here is driven, for example, by available technology for amplification components and by fiber transmission loss characteristics which give minimum fiber loss at about 1565nm. Hence, the loss in the two bands is approximately equal for the fiber between the nodes of the system. Although the present invention is illustrated for use with wavelengths in the C-band and L-band, it would be understood that the present invention is not so limited and that other bands of wavelengths may also be utilized, for example, more bands may soon be practical between 1300 nm and 1530 nm ("S" band) on fiber in which the water loss peak has been removed. Such bands would have desirable optical dispersion characteristics for channels without having too high a loss characteristic and would be tolerant of higher launch powers compared to present non-zero dispersion shifted fibers. As would be understood, optical characteristics of the single direction optical components would need to be modified accordingly.

Another advantage of the present invention is that the L and C-bands are typically separated by approximately 11nm of optical bandwidth. The use of these separated wide bands means that stimulated Brillouin scattering (which occurs with a small wavelength offset and counter propagates to the original signal direction) will not cause any penalty. This is due to the directional characteristic of the optical filters in the COMSEP units and is a characteristic not achieved using other means of signal direction such as optical circulators. In this way, the bands are well isolated from one another.

The use of the low loss single band reflection filters shown in the figure is also accompanied by appropriate design of the individual band components, e.g., optical amplifiers, multiplexers and demultiplexers, to assure that any non-ideal leakage of the other band signals do not cause degradation to desired band signals. For instance, selection of the optical amplifiers may include optimized rejection of oppositely directed alternate band signals. In general, however, the individual band components, e.g., optical amplifiers, multiplexers and demultiplexers, selected for use with the present invention are commonly available components, the source of which would be understood to a person skilled in the art.

The present invention is additionally advantageous in that having the signals in the bands travel in opposite directions improves the overall system performance as the interactions of the signals in the two bands is reduced by the fast transit time of one signal with respect to another. This minimizes the system margin that must be allocated for some types of non-linear signal corruption, for example, noise in optical receivers caused by raman coupling between optical signals.

In addition, the total optical power at any connection in the system is reduced compared to equivalent unidirectional propagation by approximately a factor of (2) two. This allows the system to realize higher performance before various hazard levels are crossed. For example, systems that have cross-sectional power levels exceeding 50 mW (approximately +17dBm) in the 1500 – 1650 nm range must utilize automatic power shutdown methods to maintain a hazard level 3A rating. As the optical power is increased, the time allowed for shutdown to complete is reduced proportionally. Thus, the present invention permits a shutdown time of nearly double the prior art for the same system total launch power in the two bands. This reduces the required design effort in other sub-systems. In addition, there are physical considerations for fiber where an event (opening a fiber connection for example) triggers a destruction of the fiber ends or can even destroy the fiber all the way back to the amplifier (source of the optical power). Some of these destructive efforts are found at power levels that practical systems employ. Others occur at levels yet to be achieved for commercial systems. The present invention allows operation to just below the threshold for these effects for nearly a factor of two in total system power. This happens because half the power is launched from each end of

the fiber and this power is typically attenuated by 3 dB (half) in 10-15 km of fiber. As long as the fiber length between nodes exceeds twice this distance (and it does as systems are usually designed for 80 km node spacing), the peak power level in a cross-section of the fiber will not significantly exceed the power level launched into the fiber from one end alone.

The foregoing description merely illustrates the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements, which, although not explicitly described or shown herein, embody the principles of the invention, and are included within its spirit and scope. For instance, it will be appreciated that the use of the C-band and L-band in the illustration of the invention is merely exemplary and that the use of other bands and sub-bands is contemplated within the scope of the present invention. More specifically, other bands including the C/S bands, and other sub-bands including the C1/C2 sub-bands may also be utilized. Also, although the unidirectional components are represented as single components, it would be understood that more than one component may be utilized to achieve the desired functionality. Furthermore, all examples and conditional language recited are principally intended expressly to be only for instructive purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

In the claims hereof any element expressed as a means for performing a specified function is intended to encompass any way of performing that function including, for example, a) a combination of circuit elements which performs that function or b) software in any form, including, therefore, firmware, microcode or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined by such claims resides in the fact that the functionalities provided by

the various recited means are combined and brought together in the manner which the claims call for. Applicant thus regards any means which can provide those functionalities as equivalent as those shown herein. Many other modifications and applications of the principles of the invention will be apparent to those skilled in the art and are contemplated by the teachings herein. Accordingly, the scope of the invention is limited only by the claims appended hereto.